Hulk edifice (Delaney et al., 1992). This core was 21 cm long. Pyrite and marcasite are the dominant minerals present, with minor amounts of wurtzite and/or sphalerite and trace amounts of galena also present. The exterior end of the core exhibits feathery barite laths intergrown with dendritic iron sulfide. In some areas barite has been replaced by amorphous silica. In mid regions of the core some of the silica exhibits a radial texture and yellow coloration similar to 2464-C01. Pyrite and marcasite exhibit massive, botryoidal, and dendritic textures, and sphalerite and/or wurtzite exhibits chalcopyrite disease. The interior end of the core is dominated by pyrite and marcasite which exhibits both dendritic and botryoidal texture. The silica in this portion of the core is clear and amorphous.

In summary, the cores provide much textural diversity resulting from the dynamic construction of the edifice wall. Porosity varies from <10 to 40%. Mineralogy is dominated by pyrite and marcasite. Amorphous silica is always present as the latest mineral phase, and varies in abundance from 1 to >50 volume %. In two of the cores some of the silica exhibits a yellow to brown coloration. Trace element analyses of this silica is in progress. There is textural evidence of relict worm tubes that have been overgrown by wall construction, and of replacement of barite by both iron sulfide and amorphous silica. Barite, a common mineral in smaller inactive structures in this area (Redding, 1992; Tivey et al., in prep), is only present in the outermost layer of the edifices where it occurs as laths intergrown with marcasite and pyrite.

REFERENCES

Delaney, J.R., V. Robigou, R.E. McDuff and M.K. Tivey, Detailed geologic relationships of a vigorous hydrothermal system: The Endeavour Vent Field, Northern Juan de Fuca Ridge, *J. Geophys. Res.* in press.

Redding, S.J., Mineralogical and textural analysis of barite-rich hydrothermal chimneys from the Endeavour Segment of the Juan de Fuca Ridge, M.S. thesis, University of South Carolina, 1992.

Robigou, V., and J. Delaney, Comparison of hydrothermal vent fields, Endeavour Segment, Juan de Fuca Ridge, *EOS Trans. AGU*, *72*, 232, 1991.

Robigou, V., J.R. Delaney, and D.S. Stakes, The High-Rise hydrothermal vent field: Endeavour Segment, Juan de Fuca Ridge, *Geology*, submitted.

Stakes, D.S., W.S. Moore, T. Tengdin, L. Holloway, M. Tivey, M. Hannington, J. Edmond and J.F. Todd, Cores drilled into active smokers on Juan de Fuca Ridge, *EOS Trans. AGU 73*, 273-283, 1992.

Tivey, M.K. and J.R. Delaney, 1986. Growth of large sulfide structures on the Endeavour Segment of the Juan de Fuca Ridge, *Earth Plan. Sci. Lett.*, *77*, 303-317.

Gold Mineralization in Seafloor Spreading Centres of the Western Pacific

Peter M. Herzig[1] and Mark D. Hannington[2]

[1]Institute of Mineralogy and Economic Geology, Aachen University of Technology, D-5100 Aachen, Germany

[2]Geological Survey of Canada, 601 Booth Street, Ottawa, Canada K1A 0E8

Since 1986, a number of sulfide deposits have been located in seafloor spreading centres of the western Pacific. Thse include the Lau Basin, North Fiji Basin, Manus Basin, Mariana Trough, Okinawa Trough, and the Western Woodlark Basin (Fig. 1).

Polymetallic sulfides from the Valu Fa Ridge in the Lau back-arc have revealed gold contents of up to 29 ppm Au with an average of 3 ppm Au (n=75). These samples are among the most gold-rich hydrothermal precipitates yet reported from the modern seafloor, and they are the first known examples of visible primary gold (up to 18 microns) in polymetallic sulfides at active vents (Herzig et al., 1990, in press). In the Okinawa Trough, gold-rich sulfide deposits with up to 14 ppm Au occur in a back-arc rift within continental crust and resemble Kuroko-type massive sulfides (Halbach et al., 1989; Urabe et al., 1990). Preliminary analyses of sulfides reported from the Central Manus Basin indicate average gold contents of 30 ppm Au (n=10) and maximum concentrations of more than 50 ppm Au. High gold contents up to 21 ppm Au have been found in barite chimneys in the Western Woodlark Basin, where seafloor spreading propagates into continental crust off Papua New Guinea (Binns et al., 1991). Sulfides in mature MORB-dominated back-arc settings such as the North Fiji Basin and the Mariana Trough contain only 0.1-1.7 ppm Au.

Gold appears to be most abundant in sulfides associated with immature seafloor rifts in continental or island arc crust. These settings are dominated by calc-alkaline volcanics including andesites, dacites, and rhyolites (i.e., Lau Basin, Okinawa Trough, Manus Basin, Woodlark Basin). Sulfide deposits related to mature back-arc spreading centres associated with MORB-type volcanics (e.g., North Fiji Basin, Mariana Trough) have gold contents which are more similar to sulfide deposits on the mid-ocean ridges.

Preliminary data suggest that the gold contents of back-arc lavas are not significantly different from those of ordinary MORB, and therefore these rocks probably do not represent an enriched source. However, the source-rock geochemistry is an important factor in controlling the composition of the hydrothermal fluids and their ability to carry gold and may be related to the buffering of the hydrothermal fluids during water-rock interaction. For example, the oxidation state of vent fluids on the mid-ocean ridges is strongly buffered by reaction with abundant FeO-bearing minerals in the rocks, and the inability of these vent fluids to become saturated with gold at high temperatures is a consequence of their low aO2 and strong redox buffering capacity. In contrast, vent fluids derived from the high-temperature reaction of seawater with more felsic lavas tend to be more oxidized and have a lower redox buffering capacity because of the lower abundance of FeO-bearing minerals in the rock. These more oxidized solutions may become saturated easily following a relatively small amount of conductive cooling, mixing, or oxidation of H_2S, and this may lead to the more efficient precipitation of gold. These observations imply that factors such as rock-buffering of the hydrothermal fluids may be as important as source considerations in generating gold-rich sulfides.

Processes which have been recognized as being important for gold enrichment in back-arc sulfides are likely to have played a role in the precipitation of gold in the ancient analogues of these deposits. Sulfide deposits in the western Pacific are indeed strikingly similar to some gold-rich massive sulfide deposits on land and may be better analogs for many ancient ore-forming systems than the deposits found on mid-ocean ridges. For example, Phanerozoic Kuroko-type deposist (Zn-Cu-Pb) closely resemble massive sulfide deposits in modern back-arc settings created by rifting of continental crust such as the Okinawa Trough, and sulfide deposits in the Eastern Manus Basin have many common characteristics with Archean Zn-Cu sulfide deposits such as the Noranda district of Canada.

Known gold-rich seafloor deposits in the western Pacific occur along the axis of a major gold belt extending from Japan through the Philippines, New Guinea, Fiji, Tonga, and New Zealand (Sillitoe, 1989). Although the porphyry-type stockworks and epithermal gold deposits in this region are

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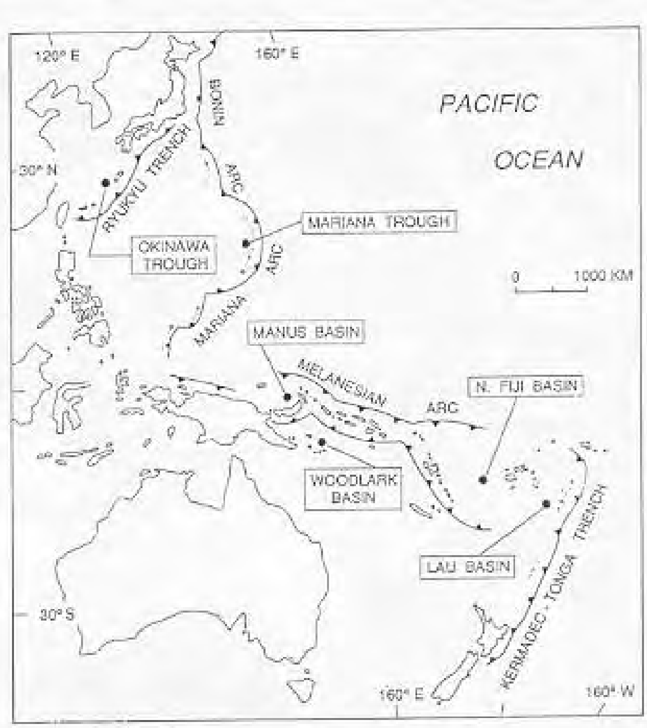

Figure 1. *Sulfide deposits in seafloor spreading centers of the western Pacific.*

Revisits to the mid-Mariana Trough Hydrothermal Site and Discovery of New Venting in the Southern Mariana Region by the Japanese Submersible *Shinkai 6500*

T. Gamo[1] and the shipboard scientific party of the Y9204 cruise: H. Chiba[2], P. Fryer[3], J. Ishibashi[4], T. Ishii[1], L.E. Johnson[5], K. Kelly[3], H. Masuda[6], S. Ohta[1], A.-L. Reysenbach[7], P.A. Rona[8], T. Shibata[9], J. Tamaoka[10], H. Tanaka[6], U. Tsunogai[4], and T. Yamaguchi[11]

[1]Ocean Research Institute, University of Tokyo, Nakano, Tokyo 164, Japan;
[2]Kyushu University; [3]University of Hawaii; [4]University of Tokyo; [5]Naval Research Laboratory; [6]Osaka City University; [7]Indiana University; [8]NOAA; [9]Okayama University; [10]JAMSTEC; [11]Chiba University

Mariana Trough is an actively spreading back arc basin behind the Mariana Trench where the Pacific plate subducts under the Philippine Sea plate (Fig.1). Horibe et al. (1986) found significant water column CH_4 anomalies above the mid-Mariana Trough, possibly due to hydrothermal activity, during the CEPHEUS Expedition of R/V *Hakuho Maru* (Ocean Research Institute, University of Tokyo, Japan) in 1982. Five years later, detailed bottom surveys using DSRV *Alvin* (Woods Hole Oceanographic Institution, U.S.A.) in the mid-Mariana Trough revealed the existence of hydrothermal activity with high temperature vent fluids (up to 287°C) and biological communities along the axial region centered on 18°13'N (the filled square in Fig.1) (Craig et al., 1987; Campbell et al., 1987; Hessler et al., 1988).

Since the *Alvin* surveys, however, no research submersible has visited this area for more than 5 years. Recent works have demonstrated that many submarine hydrothermal systems show not only spatial but also significant temporal variations (e.g., Baker et al., 1987; Lupton et al., 1989; Haymon et al., 1992). It is of much interest, therefore, to revisit the hydrothermally active sites in the mid-Mariana Trough to compare the present situations with those observed by *Alvin* in 1987. In addition, it is also of interest to visit the southern Mariana region where no submarine survey has been done so far.

The Japanese submersible *Shinkai 6500* (Japan Marine Science and Technology Center: JAMSTEC) was available for those purposes. *Shinkai 6500* and her mother ship *Yokosuka* (e.g., Auzende et al., 1992) surveyed the Mariana area between November 5 and December 1, 1992 (Y9204 cruise). Preliminary results of this

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Most of the funded projects are Phase II research efforts. Some are a natural continuation of work that did not require Phase I results. Others extend upon new discoveries made during Phase I.

Hydrothermal studies. Understanding the nature and distribution of hydrothermal activity and associated biota and sulphide minerals along the MAR was one of the principal aims enunciated in the FARA project plan. Prior to 1992, only two hydrothermal sites with their associated fauna were known on the MAR (TAG and Snake Pit). The new site near 37°15'N (Lucky Strike) has a very different geographic and tectonic setting and very different physical characteristics: it is far from the two other sites; it is in relatively shallow water; it is on relatively enriched crust associated with hot-spot influence; it is located on a prominent central seamount in the rift valley. These differences lead to many questions concerning regional geological controls (e.g., water depth, segment style) on hydrothermal and biological activity that could not even begin to be addressed before. The site has the additional advantage that it is only a day and a half from a major port (Punta Delgada), which makes it a candidate for a long-term observatory on slow-spreading crust. The short *Alvin* dive program to the Lucky Strike vent site just completed will set the stage for the *Nautile* dive programs Diva I (geology and geochemistry) and Diva II (biology), tentatively scheduled to take place in 1994. In addition to these expeditions, biological studies of the previously known hydrothermal sites at Snake Pit and TAG are being pursued (see Table 2). At another scale, the "Geofar" cruise (summer 1993) will represent a Phase I exploratory investigation of the hydrothermal record preserved in recent sediments between 20°S and the Azores.

Contrasting segment styles. A second aim of Phase I studies was to define more precisely the properties of different segment types and styles and thus obtain new quantitative data necessary to guide and ultimately test theoretical models for the origin of ridge segments and their differences. For instance, the stretch of ridge from the rift south of the Hayes FZ to the Oceanographer FZ region has good examples of end-member segments in close proximity and thus provides a convenient natural experimental area to explore the differences in bathymetry and crustal structure, gravity, volcanic expression, chemical composition, and hydrothermal activity associated with contrasting ridge segments formed at a constant spreading rate. In particular, seismic experiments to determine crustal structure and crustal thickness are needed to investigate whether the apparent differences in magmatic budget are expressed at depth. One such cruise, using the refraction method, has now been funded. Detailed geological and sampling surveys are being considered with a view to identifying differing geological and volcanological characteristics of end-member segments in this area, and to examine whether and how these differences are expressed in the petrology and petrography of the recovered rocks.

Ultramafics and methane anomalies. The 15°N region has two characteristics that, at the present time, make it uniquely interesting in terms of our current understanding of ocean ridges: it has major outcrops of serpentinite, even away from the fracture zone, and it has a large water-column signature of high methane without high Mn, a different signal than is associated with known (hot) hydrothermal vents. The ultramafic outcrops provide a so-far-unparalleled window into the upper mantle beneath the MAR. Their existence calls into question most models of ocean crust formation, and raises the issues of how well-organized the 3D petrological structure of the crust is on a regional scale and what seismic crustal thickness actually means in such a complex and tectonically disrupted terrain as much of the MAR may be. At the Cambridge symposium, investigators interested in the ultramafics of the 15°N region and the elusive sources of fluids creating the high methane concentrations concluded that additional surface ship investigations were a necessary prelude to further submersible work in the region.

Off-axis studies. Numerous problems concerning formation of mid-oceanic ridges will not be solved as long as we concentrate exclusively on zero-age crust. For example, do ridge segments have a characteristic style that is long-lived, or do they progressively evolve from one end-member style to another? How stable is the segmentation pattern, and what causes it to change? Questions such as these are fundamental to an understanding of the growth of ocean crust and the processes that control its formation. They can be addressed only by comprehensive studies that add a fourth dimension to our knowledge of the narrow window of youngest seafloor. In 1993, ONR will conduct a deep-tow cruise to the western side of the Rift north of the Kane FZ between 26°N and 27°N, and which will follow up the 1992 general survey of this area.

Further information about the FARA project may be obtained from any member of the FARA Coordinating Committee*, from the US RIDGE Office, or from the InterRidge Office.

* *M. Cannat (Fr), J. Dubois (Fr), A. Fiala-Medioni (Fr), S. Hammond (US), C. Langmuir (US Co-Chair), R. Lutz (US), H.D. Needham (Fr Co-Chair), and M. Purdy (US).*

(Herzig and Hannington, continued from page 11)

associated with island arc volcanoes (as opposed to back-arc rifts), the close proximity of modern seafloor hydrothermal systems to these volcano-plutonic arcs is striking. Active seafloor hydrothermal systems may be operating on the submerged portions of some island arc volcanoes in the western Pacific, and the potential exists for the discovery of a gold-rich massive sulfide deposit with distinctive epithermal characteristics in this environment.

REFERENCES

Binns, R.A., T. Boyd, and S.D. Scott, Precious metal spires from the Western Woodlark Basin, Papua New Guinea [abs.], *Geol. Soc. Canada, Program with Abstracts, 16*, p. A12, 1991.

Halbach, P., K. Nakamura, M. Wahsner, J. Lange, H. Sakai, L. Käselitz, R.-D. Hansen, M. Yamano, J. Post, B. Prause, R. Seifert, W. Michaelis, F. Teichmann, M. Kinoshita, A. Märten, J. Ishibashi, S. Czerwinski, and N. Blum, Probable modern analogue of Kuroko-type massive sulfide deposits in the Okinawa Trough back-arc basin, *Nature 338*, p. 496-499, 1989.

Herzig, P.M., Y. Fouquet, M.D. Hanington, and U. von Stackelberg, Visible gold in primary polymetallic sulfides from the Lau back-arc [abs.], *EOS Trans. AGU, 71*, p. 1680, 1990.

Herzig, P.M., M.D. Hannington, Y. Fouquet, U. von Stackelberg, and S. Petersen, Gold-rich polymetallic sulfides from the Lau back-arc and implications for the geochemistry of gold in seafloor hydrothermal systems of the S.W. Pacific, *Econ. Geol.* (in press), 1993.

Sillitoe, R.H., Gold deposits in western Pacific island arcs: the magmatic connection, *Econ. Geol. Mon. 6*, p. 274-291, 1989.

Urabe, T., K. Marumo, and K. Nakamura, Mineralization and related hydrothermal alteration in Izena cauldron (JADE site), Okinawa Trough, Japan [abs.], *Geol. Soc. Am., 22*, p. A9, 1990.